

Water infiltration in soils of variable bulk density with depth

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Abstract: Water infiltration in soils is one of the most important factors that must be considered in designing optimal irrigation systems. A total of twelve laboratory experiments were carried out to assess the influence of bulk density variation with depth on infiltration depth, infiltration rate, wetting front depth, and advance rate. A cylindrical soil profile of 11.43 cm diameter and 40 cm height was prepared by compacting every 10 cm of it with different bulk densities. Two types of soils (sandy loam and clay) and six sets of bulk density variations with depth (three of them were increasing and the others were decreasing) for each soil were considered. Four empirical models were developed to predict the depth of infiltration, advance of wetting front, infiltration rate, and advance rate based on time, bulk density of the upper layer, bulk density variation, and percentages of clay, silt, and sand with a high coefficient of determination. The results revealed that bulk density variation has a slight effect on water infiltration while bulk density of the upper layer has the highest effect on water infiltration. It was found that decreasing bulk density has a higher impact on infiltration than increasing bulk density, and the clayey soil is more sensitive to bulk density variation than sandy loam soil. A decrease of 7.8% and increases of 23.66%, 25.8% and 1.00% were noted in the rate of infiltration, depth of wetting front, depth of infiltration, and advance rate, respectively, for clayey soil with bulk density of the upper stratum of 1.5 g cm^{-3} and decreasing bulk density of 0.82% after 7 h of infiltration compared to those with no bulk density variation.

Keywords: soil texture; wetting front; infiltration rate; advance rate; compaction; empirical model.

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1 Introduction

Soil water movement is considered the most essential part of the hydrological cycle and an important link in the transformation of the five waters viz. groundwater, surface water, soil water, plant water and precipitation. Therefore, soil water movement plays a crucial role in the material circulation in the ecological development process (Štekauerová et al., 2006). Soil infiltration is the

process that connects groundwater, surface water and the bio-earth cycle, and affects the effective degree of soil moisture storage and the renewal of soil water. In the crop production system, soil and water are the vigorous natural resources. A high control of water infiltration in the soil will lead to efficient management of soil water. Many problems could be solved with a high control of water infiltration like pollution of surface and groundwaters, upland flooding, wastage of useful water, and inefficient irrigation of agricultural lands (Rashidi et al., 2014). By definition, infiltration is the process through which water enters the soil through the soil-atmosphere interface. Water enters the soil surface during the infiltration process under the combined

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impact of capillary and gravitational forces. Both forces act in the vertical direction to cause water to be percolated downward. Capillary forces also act to distribute water horizontally (Zhang et al., 2021). Due to its significance for issues as diverse as irrigation, pollutant transfer, groundwater recharge, and ecosystem viability, infiltration has drawn a lot of attention.

Water infiltration in soils has been considered in many field and laboratory researches. Many studies in literature such as Haghazari et al. (2015) and Xia et al. (2020) showed that infiltration process is affected by a number of factors. These factors include the properties of soil (bulk density, structure, and texture), the status of soil surface (vegetation and water head), the water application rate, the initial soil water content, the slope of soil surface, groundwater level, water temperature, soil temperature, the chemical and physical traits of the water, the soil profile status (layered or homogeneous). Fung et al. (2022) claimed that, together with waste decomposition, the infiltration of water into soils is considered to be one of the two main functions of the ecosystem and is crucial for agronomy. Five various types of urban and tropical cover (managed grass, shrubs, trees, trees with shrubs, and secondary forest) were existent in the soils where these two functions were examined. It was shown that the different types of plant cover have an influence on the infiltration process owing to the fact that the relation between infiltration rate and soil bulk density is indirect.

In nature, it is possible to note that soil profiles tend to be more heterogeneous than homogeneous in the vadose zone such as delamination with different textures (Wang et al., 2022). Yasin and Ghazal (2021) presented an empirical formula to estimate the infiltration depth based on initial soil moisture content, bulk density of soil, elapsed time, and proportions of soil components (clay, silt, and sand). They used data of 31 infiltration laboratory experiments, which involved 516 infiltration depths for various soil kinds. Based on some statistical criteria, good agreement between estimated and

measured in filtration depths was attained. They deduced that the depth and rate of infiltration reduced as a result of increasing the bulk density of the soil, increasing the initial water content of the soil, or reducing the sand content in the soil. Soil infiltration was evaluated in the field through a network of 25 sites spaced 10 meters apart by Patle et al., (2019). They found that there was a high variation in the soil textures, basic infiltration rates, bulk density, and particle density at several study sites within the field.

A direct correlation was noted between the rate of infiltration and sand content, particle density, and organic carbon content, whereas an indirect relation was found between the rate of infiltration and silt and clay content, bulk density, and water content. They also strengthened their study by developing an empirical equation to predict the rate of infiltration in terms of water content, organic carbon content, particle density, bulk density, and proportions of clay, silt, and sand.

Generally, the bulk density of field soil can vary at different depths. Before planting, the soil is usually plowed so the surface soil has lower bulk density than the subsurface soil. In contrast, after the soil has been cultivated and irrigation water has been applied, along with the movement of farmers and machinery, the soil will become compacted. As a result, the topsoil may have a higher bulk density than the subsoil, with fewer pores, reduced porosity, and changes in the distribution, shape, size, and connectivity of soil pores (Servadio et al., 2001). Therefore, the soils may be of increased bulk density with depth or vice versa. The saturated hydraulic conductivity and water infiltration rates may be greatly impacted by related influences on soil structure (Whalley et al., 2012; Basset et al., 2023). Ngo-Cong et al. (2021) used HYDRUS-1D to simulate the water infiltration into arable soils at different levels of compaction (no compaction, and 10% and 20% increase in soil bulk density). The results showed that an increase of 10%-20% in soil bulk density led to a decrease of cumulative infiltration at steady-state of 55%-82% based on soil

type. It was reported by Kim et al. (2010) that compacting a silty loam soil resulted in increase of 8% in the bulk density and decrease of 69% in the saturated hydraulic conductivity.

A field study by Al-Esawi et al. (2021) was performed to assess the impact of soil compaction and palm oil addition on the rate of water application in clayey and sandy loam soils. A plate compactor was utilized to generate three compaction phases viz. zero (no compaction), three, and five times of compactations. For oil application, two levels were considered: 0 (no oil application) and 1 L m⁻². They concluded that increasing compaction and palm oil application led to increase the bulk density in both soils. The largest bulk densities resulted from the considered treatments were 1.7 and 1.8 g cm⁻³ for clayey and sandy loam soils, respectively. Due to compaction, a reduction in infiltration rate of 73% and 86% were occurred in sandy loam and clayey soils, respectively. Additional decreases in infiltration rate were accomplished by palm oil application of 25% and 22% for the respective soils. The researchers concluded that reducing vertical infiltration through soil by the proposed method could be adopted as a water-saving technique from the bottom of the furrow and increasing the horizontal water movement to the raised bed of the furrow where the plants were grown.

The standard Kostiakov equation (Kostiakov, 1932), which is expressed by the following formula, is one of the most straightforward and often used equations for expressing the depth of cumulative infiltration with time (Patle, 2021; Gebul, 2022; Bajirao and Vishnu, 2023; Faridah et al., 2023; Jain and Chakma, 2023a; Jain and Chakma, 2023b).

$$D = ct^m \quad (1)$$

where D is the cumulative infiltration depth (mm), t is the cumulative infiltration time (min) and c , m are empirical constants.

It is obvious from the review mentioned above that water infiltration through soils is of great significance, therefore, the aim of the current study is to evaluate the influence of soils of varied bulk

density with depth on the water infiltration and wetting front advance. In addition, the impact of variable bulk density with depth of a soil profile was modeled by proposing modified empirical formulas that relating water infiltration with the affecting factors not as traditional formulas that depend only infiltration time.

2 Materials and methods

The experiments were performed in the Laboratory of Physics and Management of Soil Water that belongs to Dams and Water Resources Engineering Department, College of Engineering, University of Mosul, Mosul, Iraq. Two soil kinds (sandy loam and clay) were air dried, crushed and sieved with a 2 mm sieve. Then, the soils were gathered, spread and mixed well to attain a uniform distribution soil moisture for both soils. Next, random soil specimens were chosen to assess the initial moisture content. After reaching least variances in the values of soil water content of the chosen soil specimens, the soils were then placed inside airtight plastic bags to ensure that the moisture was evenly distributed and to maintain their initial moisture content. To determine the soil texture of the considered soils, the hydrometer method was utilized to find the percentages of sand, silt and clay of each soil (Moorberg and Crouse, 2021) then the soil texture was known by the USDA (United States Department of Agriculture) soil triangle (Table 1). In order to conduct the laboratory experiments, a plexiglass cylinder of 11.43 cm inner diameter and 45 cm height with a supported metal frame was used (Figure 1a). The cylinder was transparent, so it was easy to monitor the water advance through the soil. The cylinder had standard holes on its sides and bottom to ensure that the soil air got out freely and facilitated the flow of water into the soil.

The soil profile for each test was of 40 cm height and it was prepared by compacting the soil in the manner of layers of 5 cm thick according to the initial soil moisture and the bulk density. Each 10 cm of the soil profile had a different bulk density, so a total of

four bulk densities were considered for each soil. Two cases for the bulk density were taken into account i.e., increased bulk density with depth (downward) or vice versa. The bulk density gradient – computed as percent – was calculated by taking the difference between the values of bulk density of the bottom and surface layers divided on 30 cm which is the distance from center to center of these layers.

Therefore, if the bulk density gradient is positive that means the bulk density is increasing with depth downward and vice versa. Six bulk density gradients were considered for each soil, so a total of 12 experiments were performed. Table 1 illustrates the soil properties and the bulk density gradients for the tests.

Table 1 Summary of infiltration tests and soil properties

Test No.	Soil Texture	Bulk Densities of soil profile (up to down), g cm ⁻³	Bulk Density Gradient %	Initial Soil Moisture
1	Sandy Loam (Sand 61%, Silt 27%, Clay 12%)	1.40, 1.49, 1.59, 1.68	0.93	4.50%
2		1.54, 1.59, 1.63, 1.68	0.47	
3		1.40, 1.46, 1.53, 1.59	0.65	
4		1.68, 1.59, 1.49, 1.40	-0.93	
5		1.54, 1.49, 1.45, 1.40	-0.47	
6		1.68, 1.61, 1.55, 1.48	-0.65	
7		1.30, 1.39, 1.48, 1.56	0.87	
8	Clay (Sand 22%, Silt 34%, Clay 44%)	1.30, 1.36, 1.42, 1.49	0.61	12.2%
9		1.43, 1.48, 1.52, 1.56	0.43	
10		1.56, 1.48, 1.39, 1.30	-0.87	
11		1.56, 1.50, 1.44, 1.38	-0.61	
12		1.43, 1.39, 1.35, 1.30	-0.43	

Note: * Bulk density gradient can be calculated via $100 \times (\text{bulk density of lower layer} - \text{bulk density of upper layer}) / 30$

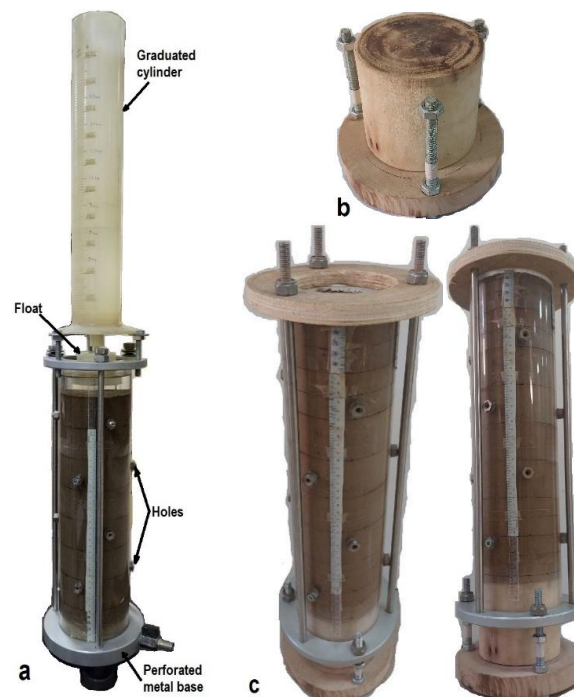


Figure 1 The soil cylinder used in laboratory experiments

Note: a is the whole setup during the experiments; b is the cylindrical wood used in preparing the soil profile of decreased bulk density with depth; c is the arrangement of the soil cylinder when preparing the soil profile of decreased bulk density with depth

All laboratory experiments were conducted using tap water, which was kept at a constant $21^{\circ}\text{C} \pm 2^{\circ}\text{C}$. A plastic-graded cylinder with a float at the bottom was used to provide water to the soil after it had been

placed on the soil cylinder. To prevent surface erosion and regulate the infiltration process's start time, a thin sheet of nylon plastic was placed over the soil's surface. During the experiment, a 3 cm water

head was applied to the soil's surface. After the thin plastic piece was removed and the water touched the soil surface, the experiment began. The depth of the wetting front in the soil was observed at certain intervals, initially close together and gradually becoming more spaced out over time.

In order to take the measurements throughout the experiments, the following procedure was followed: at specific times – monitored by a stop watch – during the experiments, the volume of infiltrated water was measured by reading the water level in the graduated cylinder. The difference between two consecutive readings was the volume of the infiltrated water, which can be divided on the internal sectional area of the soil cylinder to determine the infiltration depth. For the same specific times of infiltration measurements, the depths of wetting front were measured by monitoring them through the transparent cylinder and by the help of a transparent ruler that fixed on the external wall of the cylinder. All the experiments were stopped when the wetting front reached a little bit before the end of the soil profile.

It is worth mentioning to refer to the technique used to prepare the soil profile. The soil profile of the increasing bulk density with depth was prepared normally by compacting the first 10 cm of the soil profile that has the maximum bulk density beginning from the bottom of the soil cylinder. Then, the second 10 cm of the soil profile (from the bottom of the soil cylinder) was compacted according to its bulk density and so on until reaching the fourth 10 cm, which has the minimum bulk density. A novel method was followed to prepare the soil profile of the decreasing bulk density with depth. It was prepared by putting a cylindrical wood (Figure 1b) as a base at the top of the cylinder then flipping the cylinder to make its original base to the top. The perforated original base of the cylinder was removed to make the cylinder open from the top to add the soil (Figure 1c). The same procedure mentioned above for preparing the soil profile of increasing bulk density with depth then followed until reaching the top of the cylinder. Next, the original perforated base of the cylinder returned to

its place carefully and the cylinder flipped again to make its original base at the bottom. After that, the cylindrical wood was removed to get a soil profile of decreasing bulk density with depth.

3 Results and discussion

Table 2 shows the infiltration time, infiltration depth, and wetting front depth for all the experiments. In general, different times are needed to conduct the experiments owing to the differences in bulk density gradients, bulk density of the upper layer, and soil textures. Furthermore, water flow in soils of increasing bulk density with depth (+ve bulk density gradient) requires a shorter time than in soils of decreasing bulk density with depth (-ve bulk density gradient) for both considered soil textures. This is mainly due to the ease of water entry to a soil profile of low bulk density of the upper layer than a soil profile of high bulk density of the upper layer. This leads to the conclusion that the upper layer controls the flow of water through the soil. However, there is an exception for experiments 9 and 12 (clayey soil) as they have the same bulk density of the upper layer but experiment 9 has a +ve bulk density variation while experiment 12 has a -ve bulk density variation so the impediment of water flow is less which led to shorter test time.

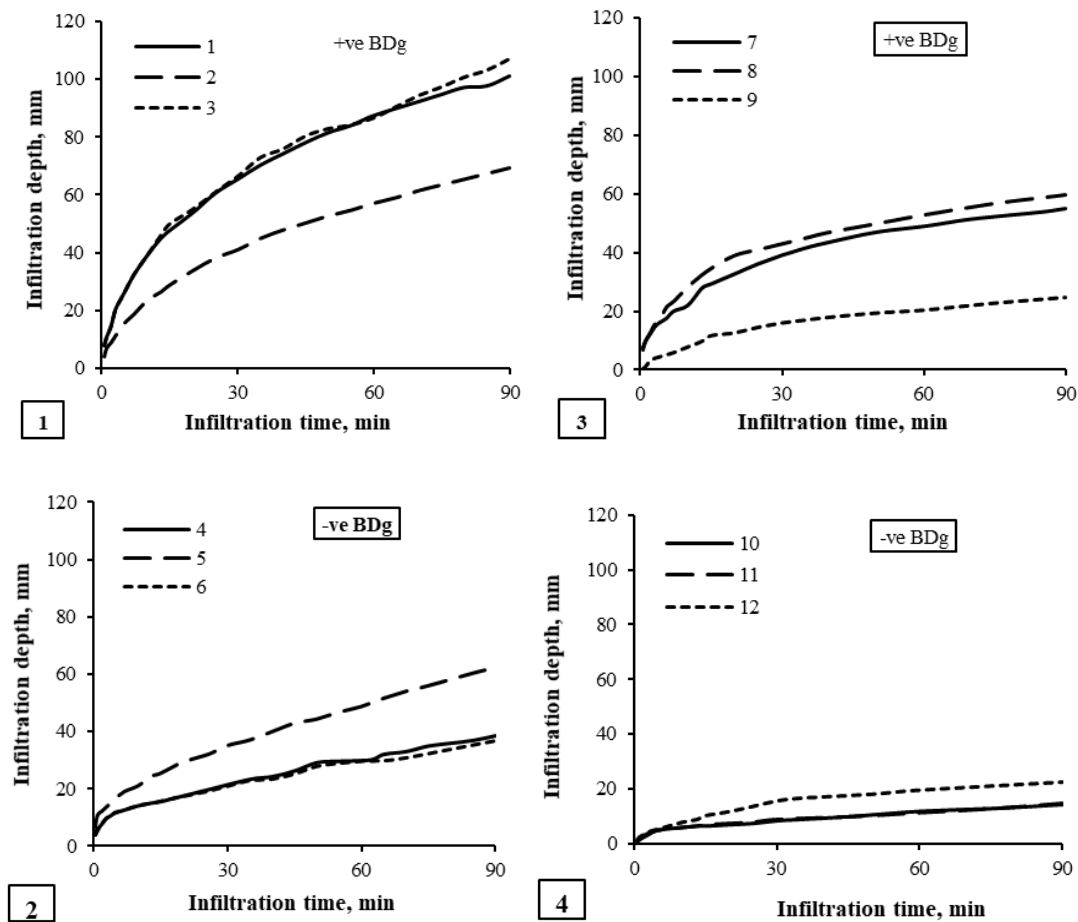
As the test times are different, it is necessary to select a common time which is 90 min to do comparisons among various cases. Figures 2 and 3 illustrate the infiltration depth and wetting front depth with time, respectively for all the experiments at a time of 90 min. It is obvious from these figures that experiments of the same bulk density of the upper layer have little difference between the depths of infiltration and wetting front although there is a difference in a bulk density gradient. These couple of experiments are (1, 3) and (4, 6) for sandy loam soil, and (7, 8) and (10, 11) for clayey soil. On the other hand, changing the bulk density of the upper layer leads to a clear effect on the depths of infiltration and wetting front (experiments 2 and 5 for sandy loam soil, and 9 and 12 for clayey soil). This confirms that

the bulk density variation with depth has a slight influence on the infiltration depth and wetting front depth for soil profiles having the same bulk density of the upper stratum. The effect of the bulk density variation with depth on the depth of infiltration and the depth of the wetting front is clear when it changes from positive to negative. For instance, changing the bulk density variation for sandy loam soil from 0.93

(experiment 1) to -0.93 (experiment 4) led to a decrease in the infiltration depth by about 40 mm for the elapsed time of 90 min (Figure 2A1 and 2A2). For more analysis and discussion of the effect of the bulk density variation with depth on infiltration and wetting front depths, the following sections include developing empirical models that combine the influence of various factors.

Table 2 Infiltration time, infiltration depth, and wetting front depth for all the experiments

No.	Soil Texture	Bulk Densities of soil profile (up to down) (g cm ⁻³)	Bulk Density Gradient (%)	Test time (min)	Infiltration depth (mm)	Wetting front depth (mm)
1	Sandy Loam	1.40, 1.49, 1.59, 1.68	0.93	100	104.3	378
2		1.54, 1.59, 1.63, 1.68	0.47	150	89.7	375
3		1.40, 1.46, 1.53, 1.59	0.65	90	107.2	380
4		1.68, 1.59, 1.49, 1.40	-0.93	290	83.8	367
5		1.54, 1.49, 1.45, 1.40	-0.47	180	98.4	375
6		1.68, 1.61, 1.55, 1.48	-0.65	290	85.8	372
7		1.30, 1.39, 1.48, 1.56	0.87	320	81.9	335
8	Clay	1.30, 1.36, 1.42, 1.49	0.61	313	97.5	360
9		1.43, 1.48, 1.52, 1.56	0.43	1030	78.9	351
10		1.56, 1.48, 1.39, 1.30	-0.87	1680	80.4	373
11		1.56, 1.50, 1.44, 1.38	-0.61	2450	71.6	393
12		1.43, 1.39, 1.35, 1.30	-0.43	540	81.4	365

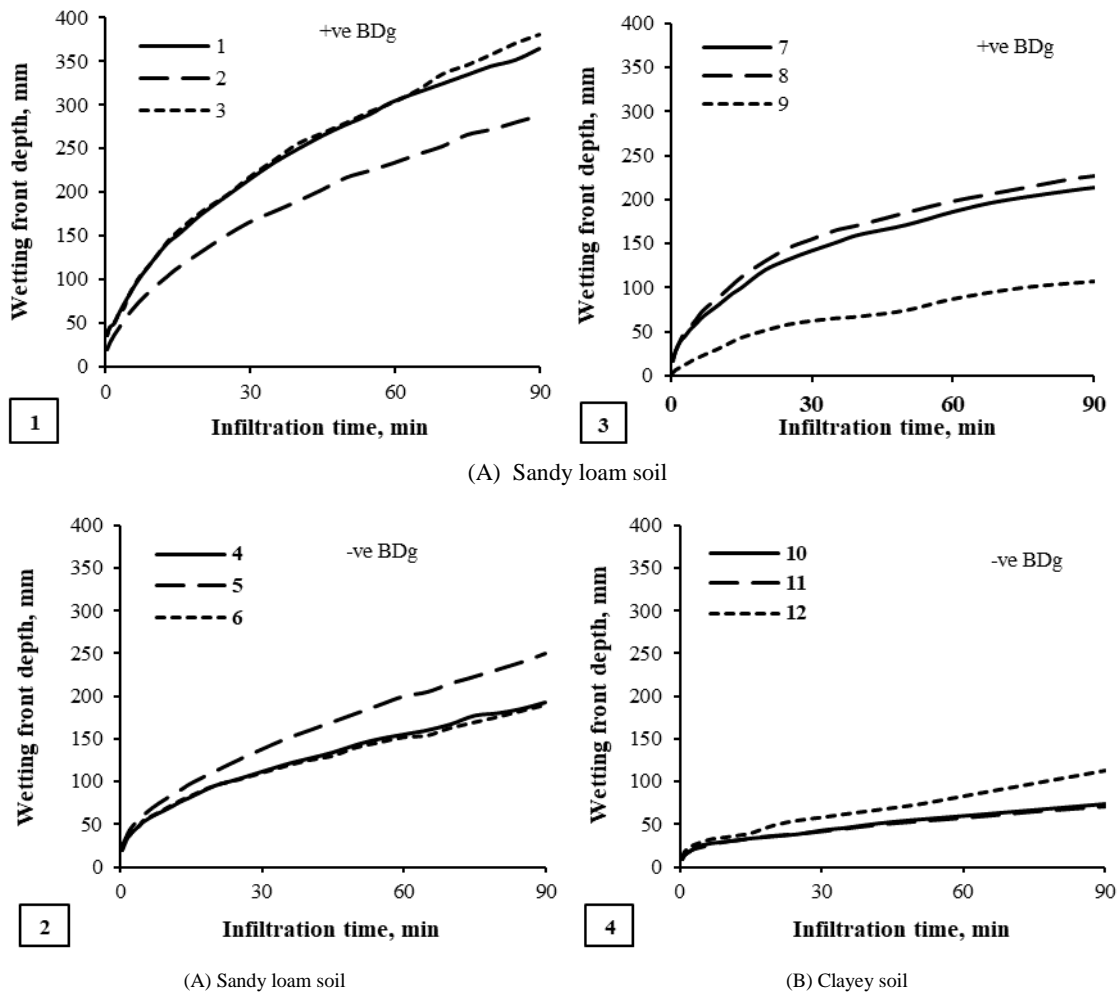


(A) Sandy loam soil

(B) Clayey soil

* BDg: is the bulk density gradient. When +ve refers to increasing and vice versa; Numbers 1 – 12 refer to the 12 experiments and their details as shown in Table 1

Figure 2 Infiltration depth with time for all experiments



(A) Sandy loam soil

(A) Sandy loam soil

(B) Clayey soil

* BD_g: is the bulk density gradient. When +ve refers to increasing and vice versa; Numbers 1 – 12 refer to the 12 experiments and their details as shown in

Table 1

Figure 3 Wetting front depth with time for all experiments

3.1 Deriving empirical models for infiltration depth and wetting front depth

Based on the results of the laboratory experiments, an empirical formula was proposed to predict the depth of cumulative infiltration (D , mm) in terms of infiltration time (t , min), bulk density of upper layer (ρ_b , g cm⁻³) in, bulk density gradient (BD_g), and the proportions of clay (C), silt (Si), and sand (Sa) as fractions, of the soil as illustrated in Equation 2:

$$D = 4.011t^{0.44}(11.452Sa + 18.076Si + 3.78C - 6.452\rho_b + 0.073BD_g) - 0.025\rho_b \cdot BD_g \cdot t \quad (2)$$

Likewise, another empirical equation was derived to estimate the wetting front depth (Z , mm) in form similar to that of Equation 2:

$$Z = 6.48t^{0.473}(36.556Sa - 13.43Si + 35.724C - 6.452\rho_b + 0.073BD_g) - 0.025\rho_b \cdot BD_g \cdot t \quad (3)$$

A total of 429 measured values were used to predict the coefficients of the Equations 2 and 3 using

the analysis of non-linear regression performed by SPSS (Statistical Package for the Social Sciences) with high determination coefficients of 0.969 and 0.985 for D and Z , respectively at P-value of 0.05. Figure 4 shows the relation between the predicted and measured values of depths of infiltration and wetting front. Deriving Equation 2 with respect to time yields the infiltration rate (I , mm h⁻¹):

$$I = 105.876t^{-0.56}(11.452Sa + 18.076Si + 3.78C - 6.452\rho_b + 0.073BD_g) - 0.025\rho_b \cdot BD_g \quad (4)$$

In analogy to infiltration rate, it is possible to develop an equation to study the advance rate (R , mm h⁻¹) of the wetting front in the soil by deriving Equation 3 with respect to time to get the following equation:

$$R = 184.097t^{-0.527}(36.556Sa - 13.43Si + 35.724C - 11.592\rho_b - 0.003BD_g) - 0.083\rho_b \cdot BD_g \quad (5)$$

Where R is the advance rate of the wetting front (mm h⁻¹).

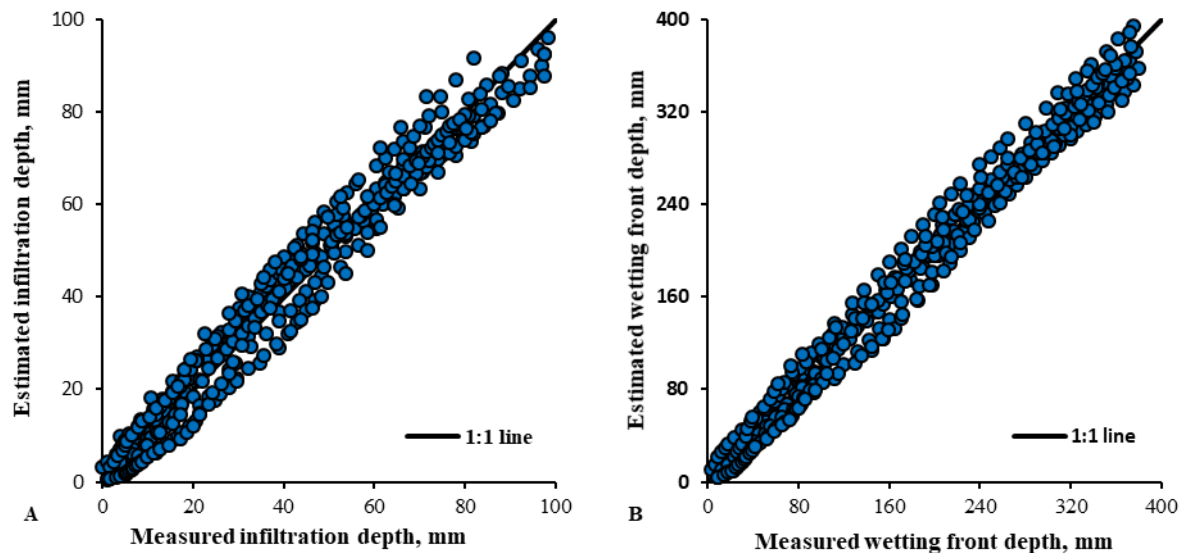


Figure 4 The relation between estimated and measured values of infiltration depths (A) and wetting front depths (B)

It is clear from Figure 4 as well as the high values of the determination coefficients that the empirical models represented by Equations 2 and 3 are good and can estimate the values of infiltration depths and wetting front depths accurately. Thus, these models with Equations 4 and 5 will be used to study the effect of variable bulk density with depth on infiltration depth, wetting front depth, and infiltration rate.

It is vital here to mention that Equations 2, 3, 4, and 5 can be applied for specific soil types (sandy loam and clay) which their properties of bulk density for each layer, bulk density gradient of the whole profile, proportions of sand, silt, and clay, thickness of the layers, and gravimetric initial moisture are shown in Table 1.

3.2 Effect of bulk density variation on infiltration depth

Figure 5A illustrates the influence of bulk density gradient with depth on infiltration depth for sandy loam soil. The bulk density variation could be decreased with depth for soil of high bulk density at upper layer (Figure 5A1) or increased with depth for soil of low bulk density at upper layer (Figure 5A2). It is obvious from Figure 5A that the bulk density of the surface stratum is the prevailing factor that affects the infiltration depth for both cases of bulk density variation. The increasing and decreasing bulk density variations with depth have a very little effect on

infiltration depth as there are slight differences among the curves of infiltration for various bulk density gradients. The bulk density gradient of -0.82 refers to a reduction of bulk density from 1.7 g cm^{-3} for the upper 10 cm to 1.455 g cm^{-3} for the lower 10 cm of the soil profile of 40 cm height. Although there is a decrease in bulk density with depth, it is evident from Figure 5A1 that there was a slight increase in infiltration depth compared to the other variations in bulk density (0, -0.35 , and -0.58) after 7 hours of infiltration. These differences are less pronounced for infiltration times less than 7 hours. The same interpretations can be applied to the case of increasing bulk density variation with depth for sandy loam soil (Figure 5A2).

Figure 5B demonstrates the impact of bulk density gradient with depth on infiltration depth for clayey soil. It is also clear that increasing or decreasing bulk density with depth resulted in a slight change in infiltration depth and the dominant factor controlling the infiltration process is the bulk density of the top stratum. The main difference between the both soils is the infiltration depth in clayey soil is less than that in sandy loam soil at the same infiltration time.

To illustrate the effect of bulk density gradient numerically, Table 3 shows the percentages of change in infiltration depth for different cases as compared to homogenous soil profile i.e. no bulk density variation.

It is clear from Table 3 that decreasing bulk density variation has higher effect on infiltration depth than increasing bulk density variation, and bulk density

variation has higher impact on infiltration depth in clayey soil than sandy loam soil.

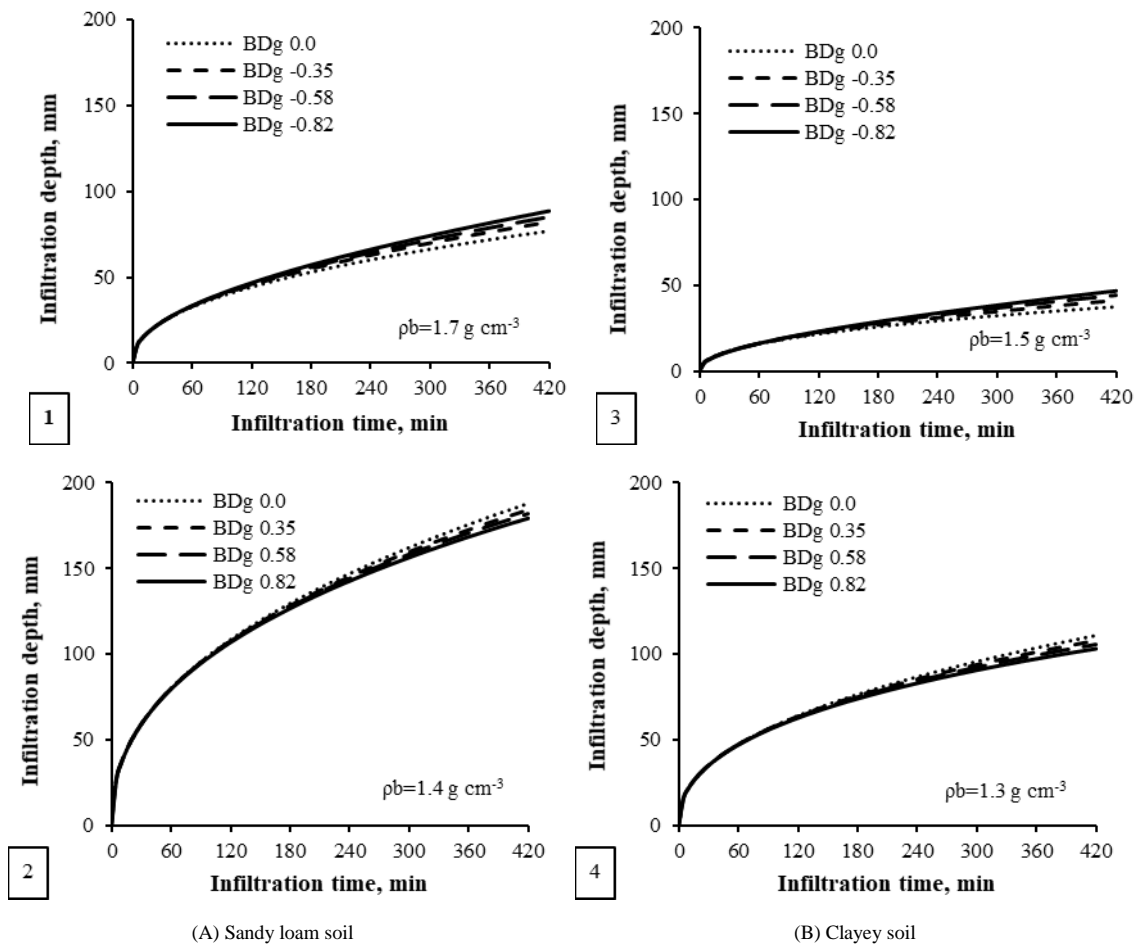


Figure 5 Effect of bulk density variation on infiltration depth for sandy loam soil (A) and clayey soil (B)

Table 3 Percentage of change in infiltration depth due to bulk density variation compared to no bulk density variation after 7 hours of infiltration time

Bulk density variation (BDg) %	Percentage of change in infiltration depth %			
	Sandy loam soil		Clayey soil	
-0.35	+ 6.29	$\rho_b = 1.7 \text{ g cm}^{-3}$	+ 11.07	$\rho_b = 1.5 \text{ g cm}^{-3}$
-0.58	+ 10.48		+ 18.45	
-0.82	+ 14.67		+ 25.82	
+0.35	- 1.99	$\rho_b = 1.4 \text{ g cm}^{-3}$	- 3.04	$\rho_b = 1.3 \text{ g cm}^{-3}$
+0.58	- 3.32		- 5.07	
+0.82	- 4.65		- 7.10	

Note: * BDg: is the bulk density gradient. When +ve refers to increasing and vice versa. ρ_b : soil bulk density of upper layer.

** The +ve and -ve sign of the change in infiltration depth refers to increase and decrease, respectively.

The influence of the bulk density of the upper layer can be shown also by comparing two different values of bulk densities of the upper layer of the same soil but having different values of bulk density gradients. Figure 6 depicts the obvious effect of the bulk density of the top layer for the same bulk density gradient for both considered soils. It can be noted from Figure 6 that the impact of the bulk density of

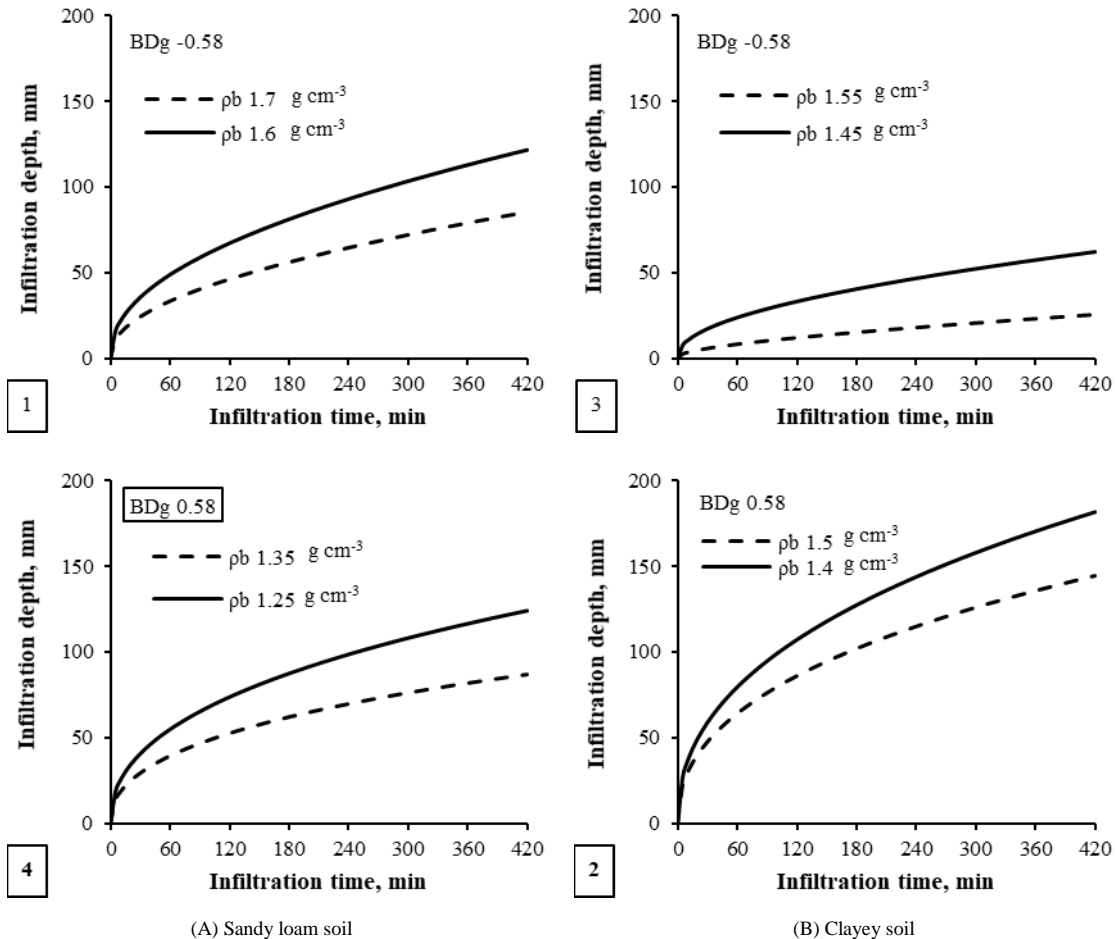
the upper layer is evident as a slight decrease in bulk density of the upper layer resulted in significant increase of the infiltration depth for the same bulk density gradient and for both considered soils. These changes in infiltration depth are shown numerically in Table 4. It is also possible to conclude that the clayey soil is more sensitive to the variation in the bulk density of the upper layer than sandy loam soil that

agrees with the study presented by Al-Esawi et al. (2021) and Ngo-Cong et al. (2021). Furthermore, the increasing bulk density gradient has lower effect on

infiltration depth than decreasing bulk density variation.

Table 4 Percentage of change in infiltration depth due to change in bulk density of the upper layer for same bulk density variation after 7 hours of infiltration time

	Sandy loam soil		Clayey soil	
Change in bulk density of upper layer, g cm^{-3}	1.7 – 1.6	1.5 – 1.4	1.55 – 1.45	1.35 – 1.25
Bulk density variation (BDg), %	- 0.58	+ 0.58	- 0.58	+ 0.58
Percentage of increase in infiltration depth, %	42.5	26.0	139.9	43.3



(A) Sandy loam soil

(B) Clayey soil

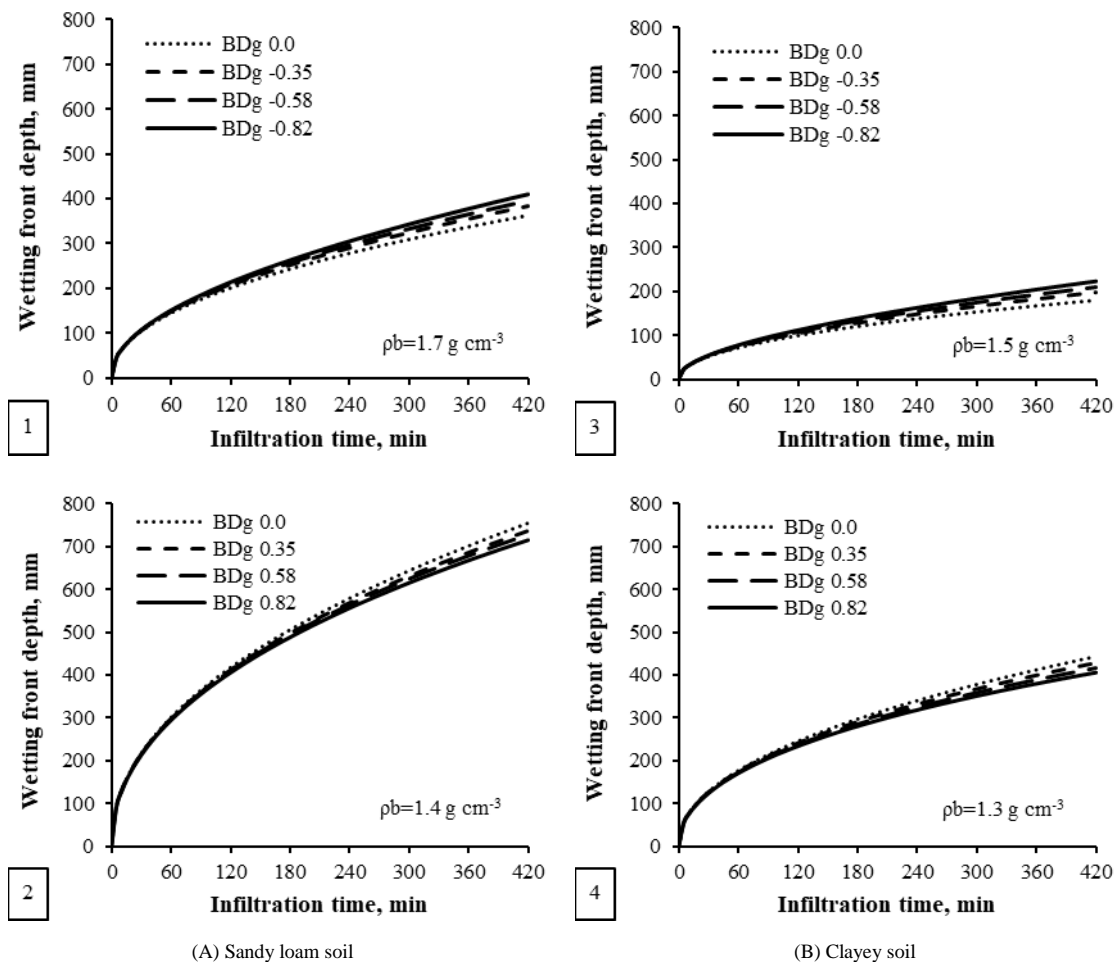
* BDg: is the bulk density gradient. When +ve refers to increasing and vice versa.

Figure 6 Effect of bulk density of the upper layer on infiltration depth for same bulk density variation for sandy loam soil (A) and clayey soil (B)

3.3 Influence of bulk density variation on depth of wetting front

The impact of decreasing and increasing bulk density gradient with depth on wetting front depth for sandy loam soil is shown in Figures 7A1 and 7A2, respectively. For both cases of bulk density variation, it is clear that the prevailing factor that affects the wetting front depth is the bulk density of the upper layer. For different bulk density gradients, slight differences among the curves of wetting front can be

noted, which let to conclude that increasing or decreasing bulk density with depth has a very little influence on wetting front depth. The highest bulk density gradient is ± 0.82 , which refers to maximum or minimum change in bulk density with depth as shown in Figure 7A. This highest bulk density gradient resulted in slight change in wetting front depth compared to the other bulk density gradients (0, -0.35, and -0.58) after 7 h of infiltration time.



(A) Sandy loam soil

(B) Clayey soil

* BDg: is the bulk density gradient. When +ve refers to increasing and vice versa.

Figure 7 Effect of bulk density variation on wetting front depth for sandy loam soil (A) and clayey soil (B)

The influence of bulk density gradient with depth on wetting front depth for clayey soil is shown in Figure 7B. A slight change in wetting front depth can be noted as a result of bulk density variation –whether increasing or decreasing– with depth. Furthermore, the bulk density of the upper stratum is the dominant factor controlling the wetting front advance. Comparing the both soils, it is clear that the wetting front depth in sandy loam soil is larger than in clayey soil at a specific infiltration time.

Table 5 shows the percentages of change in wetting front depth for different cases of bulk density gradients as compared to homogenous soil profile i.e. no bulk density variation.

It is clear from Table 5 that increasing bulk density variation has lower influence on wetting front depth than decreasing bulk density variation, and bulk density variation has lower effect on wetting front depth in sandy loam soil than clayey soil.

Table 5 Percentage of change in wetting front depth due to bulk density variation compared to no bulk density variation after 7 hours of infiltration time

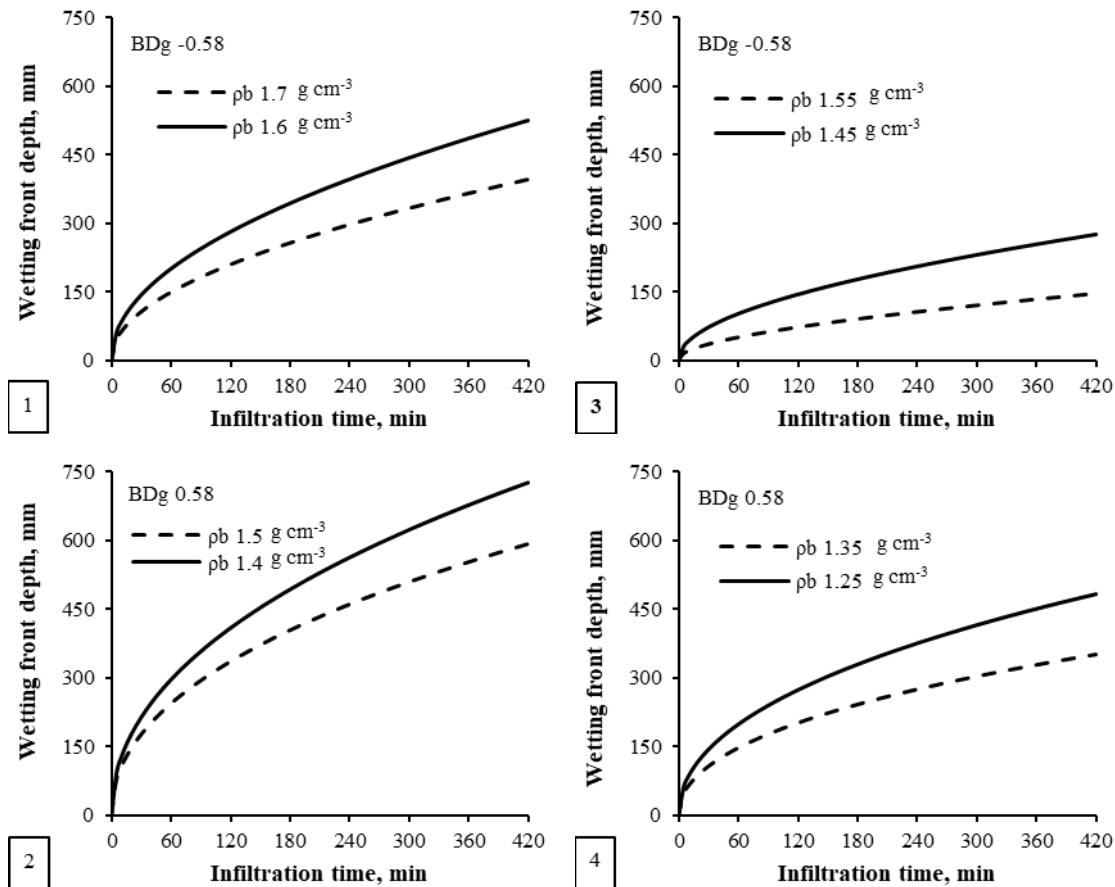
Bulk density variation (BDg) %	Percentage of change in wetting front depth %			
	Sandy loam soil		Clayey soil	
- 0.35	+ 5.74	$\rho_b = 1.7 \text{ g cm}^{-3}$	+ 10.14	$\rho_b = 1.5 \text{ g cm}^{-3}$
- 0.58	+ 9.56		+ 16.90	
- 0.82	+ 13.39		+ 23.66	
+ 0.35	- 2.27	$\rho_b = 1.4 \text{ g cm}^{-3}$	- 3.59	$\rho_b = 1.3 \text{ g cm}^{-3}$
+ 0.58	- 3.78		- 5.98	
+ 0.82	- 5.29		- 8.37	

Note: * BDg: is the bulk density gradient. When +ve refers to increasing and vice versa. ρ_b : soil bulk density of upper layer.

** The +ve and -ve sign of the change in wetting front depth refers to increase and decrease, respectively.

For same bulk density gradient for both considered soils, the apparent influence of the bulk density of the upper stratum is illustrated in Figure 8. It can be concluded that a slight increase in bulk density of the upper layer resulted in significant decrease of the depth of wetting front for the same bulk density gradient and for both considered soils. Table 6 shows the numerical changes of the wetting

front depth. It is also likely to conclude that the sandy loam soil is less sensitive to the variation in the bulk density of the upper layer than clayey soil, which concurs with Al-Esawi et al. (2021) and Ngo-Cong et al. (2021). In addition, the decreasing bulk density gradient has higher effect on wetting front depth than increasing bulk density variation.



* BDg: is the bulk density gradient. When +ve refers to increasing and vice versa.

Figure 8 Effect of bulk density of the upper layer on wetting front depth for same bulk density variation for sandy loam soil (A) and clayey soil (B)

Table 6 Percentage of change in wetting front depth due to change in bulk density of the upper layer for same bulk density variation after 7 hours of infiltration time

	Sandy loam soil		Clayey soil	
Change in bulk density of upper layer, g cm ⁻³	1.7 – 1.6	1.5 – 1.4	1.55 – 1.45	1.35 – 1.25
Bulk density variation (BDg), %	-0.58	+0.58	-0.58	+0.58
Percentage of increase in wetting front depth, %	32.4	22.4	88.1	38.1

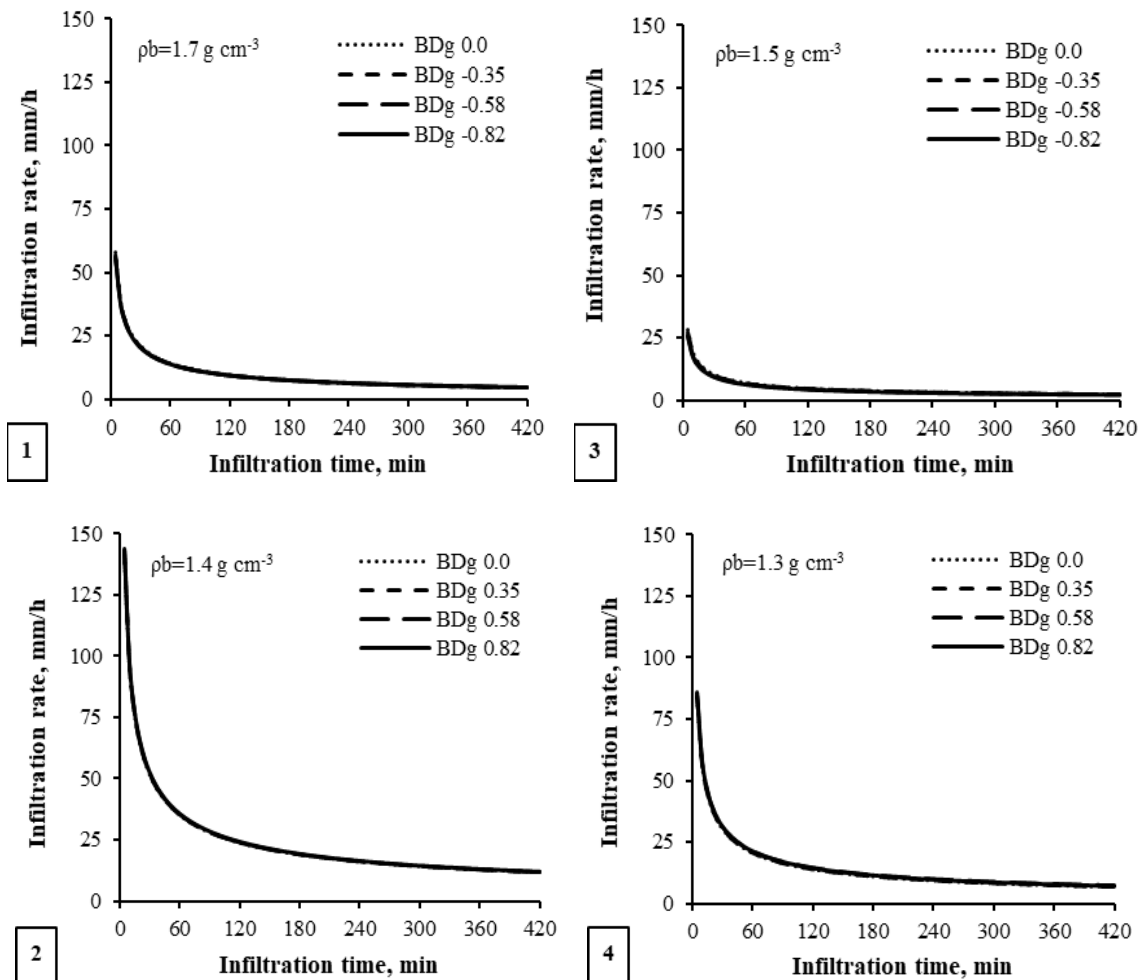
3.4 Impact of bulk density variation on the rate of infiltration

Figure 9A illustrates how the infiltration rate for sandy loam soil is affected by the bulk density gradient with depth. For soil with a high bulk density at the top layer (Figure 9A1), the bulk density variation may decrease with depth; for soil with a low

bulk density at the top layer (Figure 9A2), the bulk density variation may increase with depth. Figure 9A makes it clear that, in both situations of bulk density variation, the infiltration rate is mostly influenced by the upper layer's bulk density. Since the infiltration rate curves for various bulk density gradients hardly

differ from one another, the growing and decreasing bulk density variations with depth have very little effect on infiltration rate. The soil profile of 40 cm height has a bulk density gradient of -0.82, meaning that the bulk density decreased from 1.7 g cm⁻³ for the upper 10 cm to 1.455 g cm⁻³ for the lower 10 cm. Despite this decrease in bulk density with depth,

Figure 9A1 shows that, after 7 hours of infiltration time, there was essentially no variation in the infiltration rate among all bulk density variations. The same interpretations can be made for the case of increasing bulk density variation with depth for sandy loam soil (Figure 9A2).



* BDg: is the bulk density gradient. When +ve refers to increasing and vice versa.

Figure 9 Effect of bulk density variation on infiltration rate for sandy loam soil (A) and clayey soil (B)

For clayey soil, Figure 9B shows how the bulk density gradient with depth affects the infiltration rate; once more, it is evident that increasing or decreasing bulk density with depth did not significantly alter the infiltration rate, and that the bulk density of the upper layer is the dominant factor controlling the rate of infiltration. The primary distinction between the two soil types is that at the same infiltration time, the infiltration rate in clayey soil is lower than that in sandy loam soil.

The impact of the bulk density gradient is numerically illustrated in Table 7, which displays the

percentages of change in infiltration rate for various cases relative to a homogenous soil profile, that is, no bulk density variation. It is evident from Table 7 that the infiltration rate is more affected by decreasing bulk density variation than by increasing bulk density variation, and that the infiltration rate is more affected by bulk density variation in clayey soil than in sandy loam soil. The maximum change in infiltration rate for all cases considered did not exceed 10%, which made it difficult to distinguish between the infiltration curves in Figure 9.

Table 7 Percentage of change in infiltration rate due to bulk density variation compared to no bulk density variation after 7 hours of infiltration time

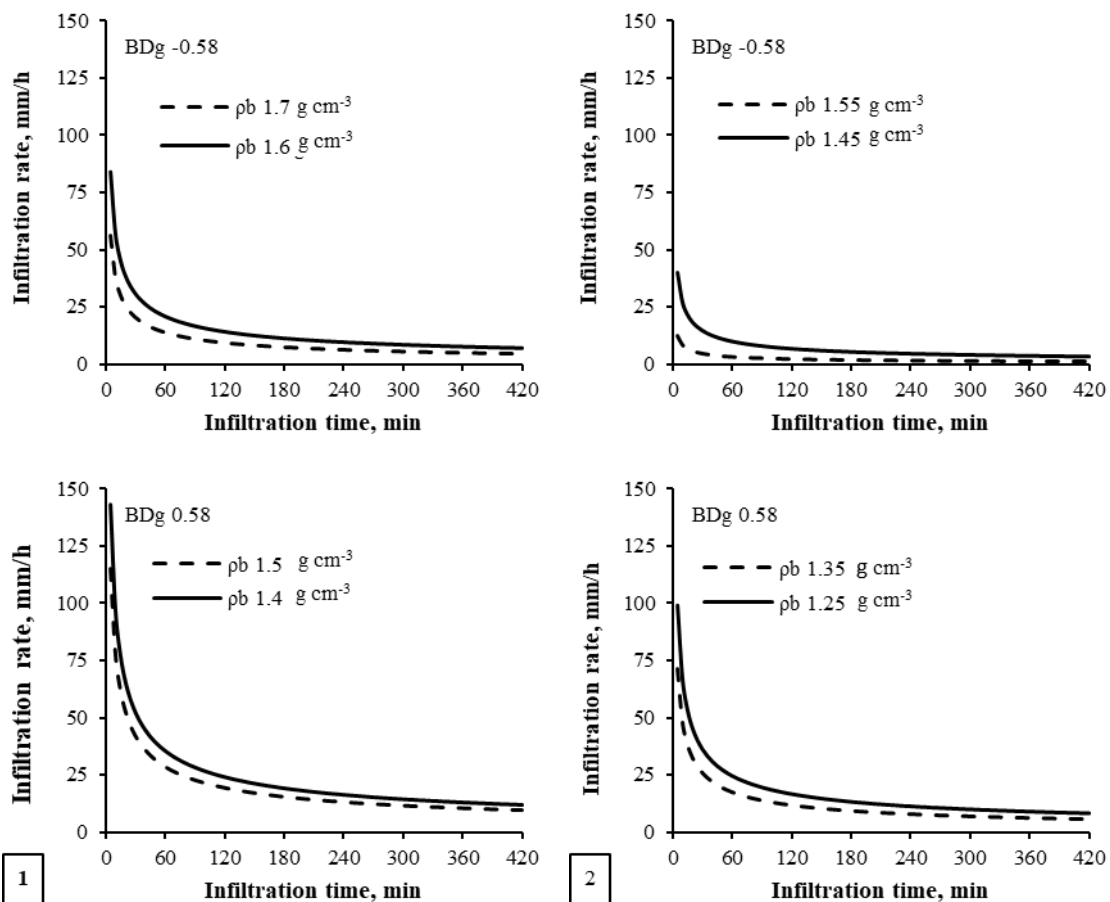
Bulk density variation (BDg) %	Percentage of change in infiltration rate %			
	Sandy loam soil		Clayey soil	
-0.35	-1.57	$\rho_b = 1.7 \text{ g cm}^{-3}$	-3.34	$\rho_b = 1.5 \text{ g cm}^{-3}$
-0.58	-2.62		-5.57	
-0.82	-3.67		-7.80	
+0.35	0.67	$\rho_b = 1.4 \text{ g cm}^{-3}$	1.15	$\rho_b = 1.3 \text{ g cm}^{-3}$
+0.58	1.11		1.91	
+0.82	1.56		2.67	

Note: * BDg: is the bulk density gradient. When +ve refers to increasing and vice versa. ρ_b : soil bulk density of upper layer.

** The +ve and -ve sign of the change in infiltration rate refers to increase and decrease, respectively.

The impact of the top stratum's bulk density can also be demonstrated by contrasting two upper-layer bulk densities of the same soil with varying bulk density gradient values. For the identical bulk density gradient for both soils under consideration, Figure 10 shows the apparent impact of the surface layer's bulk density. Figure 10 illustrates the impact of the upper layer's bulk density, showing that a little decrease in the upper layer's bulk density led to a notable increase in the infiltration rate for both soils under

consideration and for the same bulk density gradient. Table 8 provides numerical evidence of these changes in infiltration rate. It is also likely to conclude that clayey soil is more sensitive to changes in the upper layer's bulk density than sandy loam soil, which is consistent with the study by Al-Esawi et al. (2021) and Ngo-Cong et al. (2021). Additionally, the infiltration rate is less affected by an increasing bulk density gradient than by a decreasing bulk density variation.



* BDg: is the bulk density gradient. When +ve refers to increasing and vice versa.

Figure 10 Effect of bulk density of the upper layer on infiltration rate for same bulk density variation for sandy loam soil (A) and clayey soil (B)

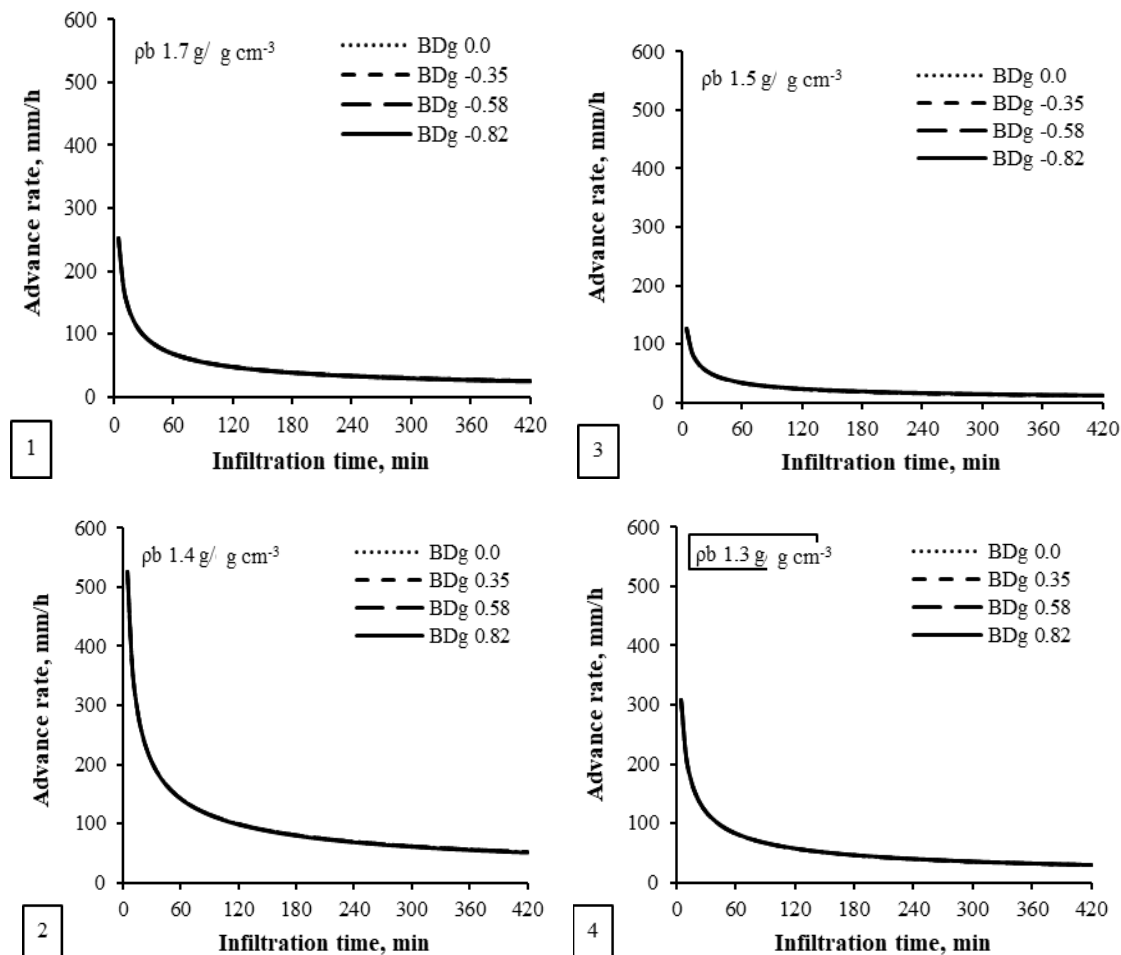
Table 8 Percentage of change in infiltration rate due to change in bulk density of the upper layer for same bulk density variation after 7 hours of infiltration time

	Sandy loam soil		Clayey soil	
Change in bulk density of upper layer, $g\ cm^{-3}$	1.7 – 1.6	1.5 – 1.4	1.55 – 1.45	1.35 – 1.25
Bulk density variation (BDg), %	-0.58	+0.58	-0.58	+0.58
Percentage of increase in infiltration rate, %	49.0	24.1	220.7	39.0

3.5 The advance rate as affected by bulk density gradient

As discussed previously for the other parameters viz infiltration depth, wetting front depth, and infiltration rate, the advance rate of the wetting front also affected by changing the bulk density gradient. Therefore, the relation between the advance rate against time for both considered soils and different values of bulk density gradients is illustrated in

Figure 11. By inspection, it is impossible to recognize any difference among the curves of advance rates for all the cases shown in Figure 11, which leads to conclude that bulk density variation had a very little influence on advance rate of the wetting front. However, it can be noted that clayey soil had advance rate lower than that for sandy loam soil. Thus, it is crucial to compare among these cases numerically as listed in Table 9 to clarify the differences.



* BDg: is the bulk density gradient. When +ve refers to increasing and vice versa.

Figure 11 Effect of bulk density variation on advance rate for sandy loam soil (A), and clayey soil (B)

The percentages of change in the advance rate owing to bulk density gradient compared to no bulk density variation at a time of 7 hours –listed in Table 9– confirm the very slight influence of bulk density variation on the advance rate as the maximum change didn't exceed 1% for all cases. It is also can be noted

by comparing the advance rate with the infiltration rate (Tables 7 and 9) that the behavior of the advance rate was opposite to the infiltration rate's behavior i.e. the advance rate increased with decreasing bulk density variation and vice versa.

Table 9 Percentage of change in advance rate due to bulk density variation compared to no bulk density variation after 7 hours of infiltration time

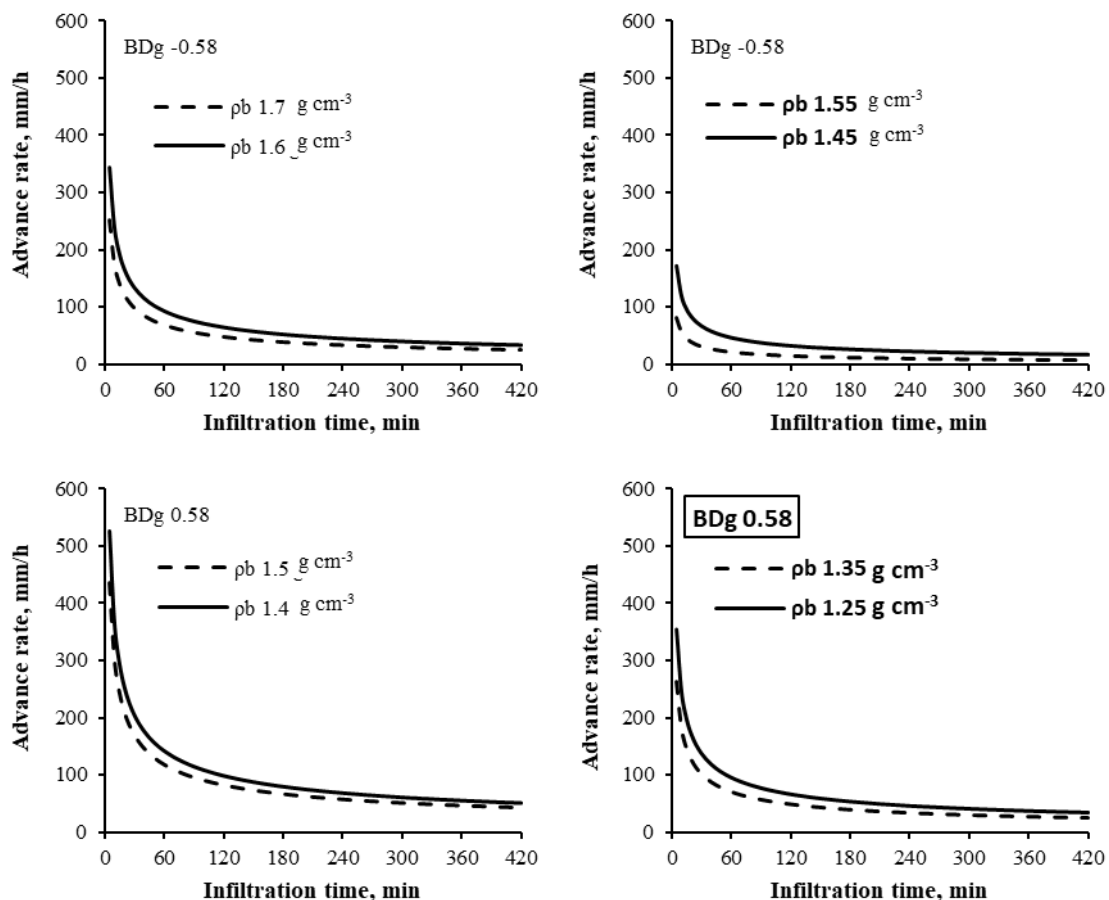
Bulk density variation (BDg) %	Percentage of change in advance rate %			
	Sandy loam soil		Clayey soil	
-0.35	0.24	$\rho_b = 1.7 \text{ g cm}^{-3}$	0.43	$\rho_b = 1.5 \text{ g cm}^{-3}$
-0.58	0.39		0.71	
-0.82	0.55		1.00	
+0.35	-0.10	$\rho_b = 1.4 \text{ g cm}^{-3}$	-0.15	$\rho_b = 1.3 \text{ g cm}^{-3}$
+0.58	-0.16		-0.26	
+0.82	-0.23		-0.36	

Note: * BDg: is the bulk density gradient. When +ve refers to increasing and vice versa. ρ_b : soil bulk density of upper layer.

** The +ve and -ve sign of the change in advance rate refers to increase and decrease, respectively.

Another comparison can also be conducted to assess the effect of changing the bulk density of the upper layer on the advance rate when keeping the bulk density gradient constant. This comparison is demonstrated in Figure 12, which illustrates the clear difference between the advance curves when the bulk density of the upper layer changed while the bulk density gradient remained constant. This agreed with the cases mentioned above for the other parameters considered in this study i.e. the bulk density of the

upper layer that the water encountered at the soil surface was the most controlling factor affects the water movement into the soil. Table 10 shows the numerical comparison among the various cases shown in Figure12. The high percentages of change in the advance rate listed in Table 10 confirmed the large effect of the bulk density of the upper layer on the advance rate that agreed with the conclusions mentioned above in the previous sections.



* BDg: is the bulk density gradient. When +ve refers to increasing and vice versa.

Figure 12 Effect of bulk density of the upper layer on advance rate for same bulk density variation for sandy loam soil (A) and clayey soil (B)

Table 10 Percentage of change in advance rate due to change in bulk density of the upper layer for same bulk density variation after 7 h of infiltration time

	Sandy loam soil		Clayey soil	
Change in bulk density of upper layer, g cm^{-3}	1.7 – 1.6	1.5 – 1.4	1.55 – 1.45	1.35 – 1.25
Bulk density variation (BDg), %	– 0.58	+ 0.58	– 0.58	+ 0.58
Percentage of increase in advance rate, %	49.0	21.1	112.6	34.9

4 Conclusions

One of the most important parameters that must be taken into account in designing optimal irrigation systems is water infiltration through the soils. The influence of variable bulk density with depth on depth of infiltration, depth of wetting front, rate of infiltration, and advance rate was evaluated by conducting 12 laboratory experiments. Four layers of 10 cm height of different bulk densities were compacted to form a cylindrical soil profile of 11.43 cm diameter and 40 cm height. Two kinds of soils (clayey and sandy loam) were used in the study. The bulk density variation with depth could be increasing for soil of low bulk density of the upper layer or vice versa. Consequently, three values of bulk density variations for each trend and for both considered soils were assessed. Two empirical equations were derived to predict depth of infiltration and depth of wetting front in terms of bulk density of the upper layer, elapsed time, bulk density variation, and proportions of sand, silt and clay of the soil with high coefficients of determination of 0.969 and 0.983, respectively. Due to the accuracy of these equations, they were used to evaluate the effect of variable bulk density with depth on water infiltration.

The results showed that an inconsiderable effect of bulk density variation on infiltration depth, wetting front depth, infiltration rate and advance rate was noted. In addition, it was concluded that the bulk density of the top layer, which it encounters the water entry, has the largest impact on depth of infiltration, depth of wetting front, infiltration rate and advance rate. The decreasing bulk density variation was found to have higher influence on water infiltration than increasing bulk density variation. Moreover, the bulk density variation has less impact on water infiltration in sandy loam soil than clayey soil. For both soils and after 7 h of infiltration and under a bulk density

variation of – 0.82%, the maximum percentages of change were achieved as compared to no bulk density variation as follows: for clayey soil of bulk density of 1.5 g cm^{-3} , a reduction of 7.8% and an increase of 25.8%, 23.7%, and 1.00% were noted in infiltration rate, infiltration depth, wetting front depth, and advance rate, respectively. Additionally, for sandy loam soil of bulk density of 1.7 g cm^{-3} , a reduction of 3.7% and an increase of 14.7%, 13.4%, and 0.6% were noted in infiltration rate, infiltration depth, wetting front depth, and advance rate, respectively.

This research presents an opportunity for future studies, as recommendations, such as the change in the moisture content of the layers, the thickness of the layers, other types of soils, deriving equations on an analytical or numerical basis and considering the hydraulic properties of the soil, and other conditions.

Data Availability Statement

All data, models, and code generated or used during the study appear in the submitted article.

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